AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1002/2015JD023960

Key Point:

- Lightning flash spatial characteristics with strong diurnal component

Correspondence to:
T. Chronis,
themis.chronis@nsstc.uah.edu

Citation:
Chronis, T., T. Lang, W. Koshak, R. Blakeslee, H. Christian, E. McCaul, and J. Bailey (2015), Diurnal characteristics of lightning flashes detected over the São Paulo lightning mapping array, *J. Geophys. Res. Atmos.*, *120*, 11,799–11,808, doi:10.1002/2015JD023960.

Received 18 JUL 2015
Accepted 21 OCT 2015
Accepted article online 26 OCT 2015
Published online 1 DEC 2015

Diurnal characteristics of lightning flashes detected over the São Paulo lightning mapping array

T. Chronis[1], T. Lang[2], W. Koshak[2], R. Blakeslee[2], H. Christian[1], E. McCaul[3], and J. Bailey[1]

[1]Earth System Science Center, University of Alabama in Huntsville, Huntsville, Alabama, USA, [2]NASA Marshall Space Flight Center, Huntsville, Huntsville, USA, [3]Universities Space Research Association, Huntsville, Huntsville, USA

Abstract This study examines diurnal variations of lightning flash characteristics observed by the Lightning Mapping Array in São Paulo, Brazil. The diurnal flash counts exhibit the typical afternoon convective maximum. The mean source altitude demonstrates a discrete increase that is temporally coincident with the local sunrise. The mean horizontal and vertical flash extents each attain a maximum (minimum) around local sunrise (afternoon, i.e., 13:00–17:00 local solar time). In addition, joint histograms of flash horizontal and vertical extents show that the majority of the flashes occurring during the afternoon convection are shorter and more comparable in size, and the differences between the horizontal and vertical extents are reduced. Conversely, flashes preceding and following the peak in afternoon convection are less symmetric, with larger horizontal than vertical extents. We discuss whether these observations could be partially explained by the diurnal variations in the convectively induced mixing regimes that control thundercloud charge regions and associated charge separation distances. The documented diurnal flash characteristics closely match recently published findings on the diurnal variation of the peak currents of cloud-to-ground flashes. Possible physical mechanisms for these observations are discussed.

1. Introduction

The temporal and regional variations in lightning flash characteristics are ultimately linked to the spatial scales at which they are studied. On the storm scale, the temporal variation of lightning flash rates exhibits an in-phase behavior with parameters such as updraft, graupel, and ice flux [*Goodman et al.*, 1988; *MacGorman and Morgenstern*, 1998; *Saunders et al.*, 2006; *Emersic and Saunders*, 2010; *Carey and Rutledge*, 2003; *Deierling and Petersen*, 2008; *Schultz et al.*, 2011; *Bruning and MacGorman*, 2013; *Chronis et al.*, 2015a]. On a regional scale, lightning flash rate is related to the diurnal solar heating [*Williams and Heckman*, 1993; *Williams et al.*, 2000; *Orville and Huffines*, 2001; *Mach et al.*, 2011; *Cecil et al.*, 2014; *Blakeslee et al.*, 2013]. Studies over the United States [*Changnon*, 1988; *Zajac and Rutledge*, 2001; *Orville and Huffines*, 2001; *Carey and Rutledge*, 2003; *Rudlosky and Fuelberg*, 2010; *Villarini and Smith*, 2013; *Holle*, 2014] and other parts of the world [*Pinto et al.*, 1999; *Chronis et al.*, 2007; *Christian et al.*, 2003; *Abarca et al.*, 2010; *Chronis*, 2012; *Said et al.*, 2013] confirm that the diurnal cloud-to-ground (CG) and intracloud (IC) lightning flash rates over land typically exhibit a local afternoon maximum.

Surprisingly, lightning flash-related characteristics other than counts (or rates) have been only sparingly covered by the current literature [*Pinto et al.*, 2003; *Abarca et al.*, 2010; *Mach et al.*, 2010, 2011; *Beirle et al.*, 2014; *Holle*, 2014; *Blakeslee et al.*, 2013; *Chronis et al.*, 2015b]. Recent results by *Bruning and MacGorman* [2013] demonstrate that the flash activity and flash spatial characteristics are strongly interrelated variables on the storm scale via the turbulence regime (i.e., environments having stronger turbulence produce smaller flash sizes and vice versa).

Along these lines, and also following the arguments made in *Chronis et al.* [2015b], this study postulates that a diurnal component (i.e., local solar hour) might also be evident in the spatial flash characteristics. This could be understood as follows: During the early morning hours the mixed layer is constrained by the nocturnal temperature inversion. In the presence of the gradual increase of shortwave radiation after sunrise, the associated increase of vertical mixing induced by thermals gives way to rapid mixed-layer vertical growth (~50–100 m/min) yielding higher cloud bases [*Soden*, 2000; *Betts et al.*, 2002; *Zhang and Klein*, 2013]. Latent heat release eventually enables the updraft parcels to break through the capping inversion allowing them to reach the freezing level so that lightning can occur (i.e., as seen by the onset of very high frequency (VHF)-related lightning sources, also shown later in this study). Although deviations from this behavior on a storm scale may be present, from a climatological

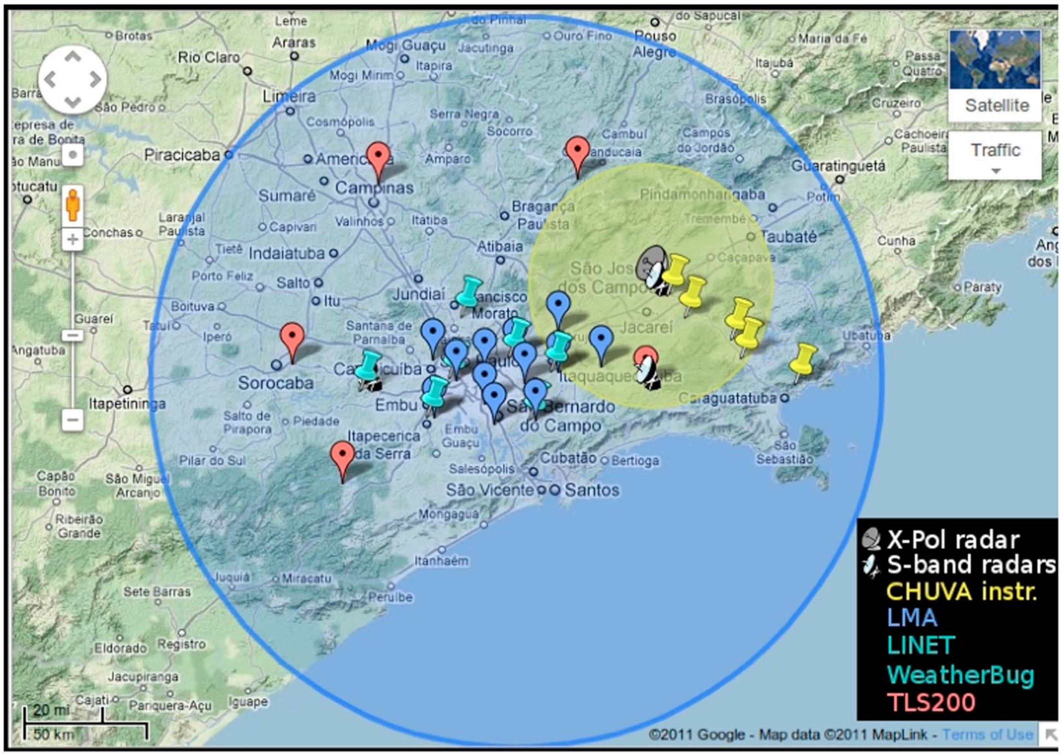

Figure 1. The locations of the SP LMA sensors. Adapted from *Blakeslee et al*. [2013]. The blue circle indicates a 150 km radius around the SP LMA network.

perspective, the morning (afternoon) storms are expected to relate to weaker (stronger) turbulence regimes not only in the updraft core but also in its peripheral region. Arguably, the climatological diurnal behavior of turbulence regimes might also enforce additional effects on the thundercloud charges spatial distribution and consequently the flash spatial characteristics. For example, due to the preponderance of high vertical mixing in the afternoon storms, one could speculate that the collisions between graupel and ice particles in the presence of supercooled water [*Takahashi*, 1978; *Saunders*, 1993] are more frequent; hence, the distances between the electrostatic thundercloud charges are expected to be smaller (in the context of smaller eddies caused by the stronger turbulence). In contrast, the late night or morning storms are expected to exhibit more laminar charge distribution that frequently occurs within convective remnants or frontal storms controlled by the horizontal advection from the midlevel and upper level. This study's testable hypothesis will be framed around the diurnal component that the VHF-flash composing sources might exhibit.

2. Data and Methodology

With the advent of ground-based lightning mapping systems we now have access to a much broader spectrum of information than the flash's time and location. The Lightning Mapping Arrays (LMAs, *Rison et al*., 1999) provide information about the 3-D spatial distribution of the VHF radiation emitted during the processes that make up a lightning flash (e.g., the initial breakdown, leader propagation, and other K-processes [*Thomas et al*., 2004; *Koshak et al*., 2004]).

In this study we examine data from the São Paulo, Brazil, LMA (SPLMA [*Blakeslee et al*., 2013; *Machado et al*., 2014]), composed of 12 stations deployed in October 2011 [*Bailey et al*., 2011] in support of the CHUVA field campaign (CHUVA—*Cloud processes of tHe main precipitation systems in Brazil*: *A contribUtion to cloud resolVing modeling*; Figure 1). The study period extends from 24 October 2011 to 3 April 2012. The location accuracy is range-dependent but is relatively constant within ~100 km radius from the SPLMA network center (typical RMS error ~50–60 m [*Thomas et al*., 2004; *Koshak et al*., 2004]). Lightning flashes are determined from the SPLMA network data by clustering at least 5 VHF radiation points (hereafter sources) using both time

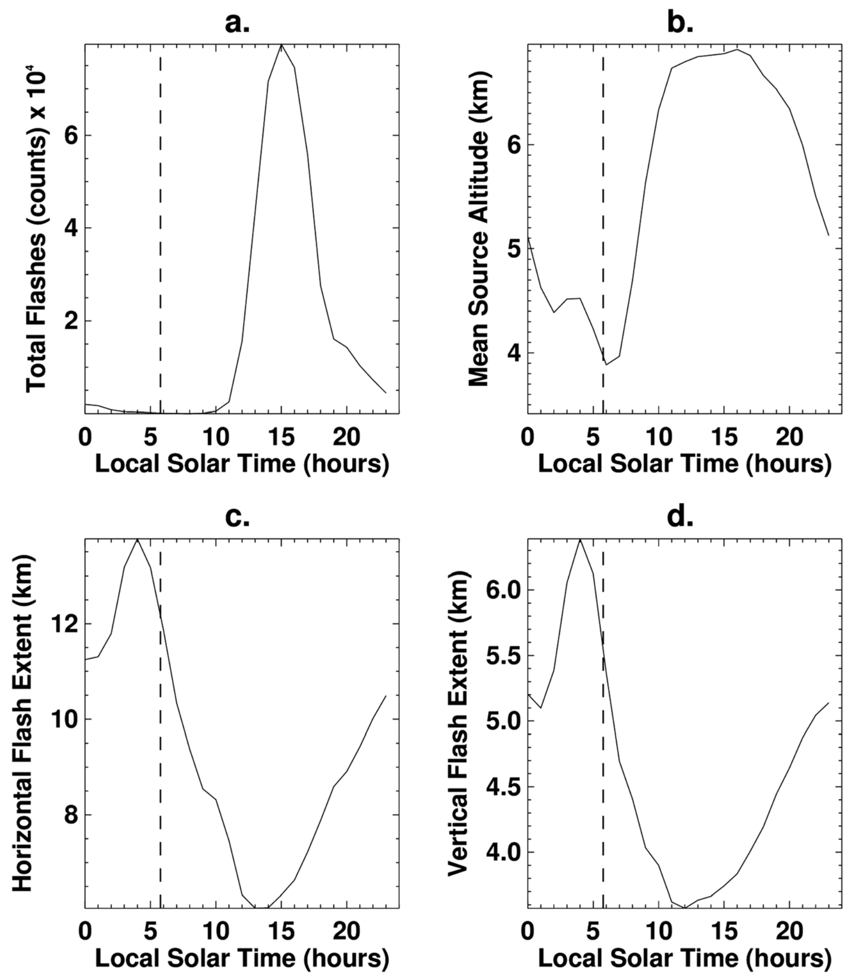

Figure 2. Two-hour running averages of the diurnal variation (LST, *x* axis in hours) of (a) flash counts (*y* axis, counts), (b) mean of the flash-composing source altitudes (*y* axis, kilometer), (c) mean horizontal flash extent distribution, and (d) mean vertical flash extent distribution. Given the temporal span of the study we consider the average local sunrise around 06:00. This is indicated by the vertical dashed line.

and space constraints (3 km and 150 ms) between adjoining flash sources [*McCaul et al*., 2009]. We consider only sources detected by at least 6 SPLMA sensors with solutions having chi-square < 0.5 [*Thomas et al*., 2004]

Within a distance of 80 km from the SPLMA network center, 429,536 flashes are identified during the study period. For these flashes we compute the following averages within each of the 24-hourly local solar time (LST) bins: (1) mean source altitude, (2) horizontal extent, and (3) vertical extent. The flash horizontal (vertical) extent represents the maximum horizontal (vertical) distance found between the groups of sources defining a flash. Note that the LST hourly binning pertains to each flash individually.

3. Results

The diurnal flash variation (i.e., counts; Figure 2a) exhibits an increasing trend after ~10:00 LST, reaching an hourly maximum around 15:00 LST (102,512 flashes). Thereafter and until the morning hours (~10:00 LST), the total number of hourly flashes declines to ~40–500 (03:00–09:00 LST). The flash diurnal variation shown in Figure 2a is also in agreement with numerous ground and space-based global observations [e.g., *Pinto et al*., 1999; *Chronis*, 2012; *Holle*, 2014].

Interestingly, we observe that the flash-size related parameters (Figures 2b–2d) also exhibit a pronounced diurnal component. In particular, the diurnal variation of the VHF source altitudes (Figure 2b) exhibits a clear

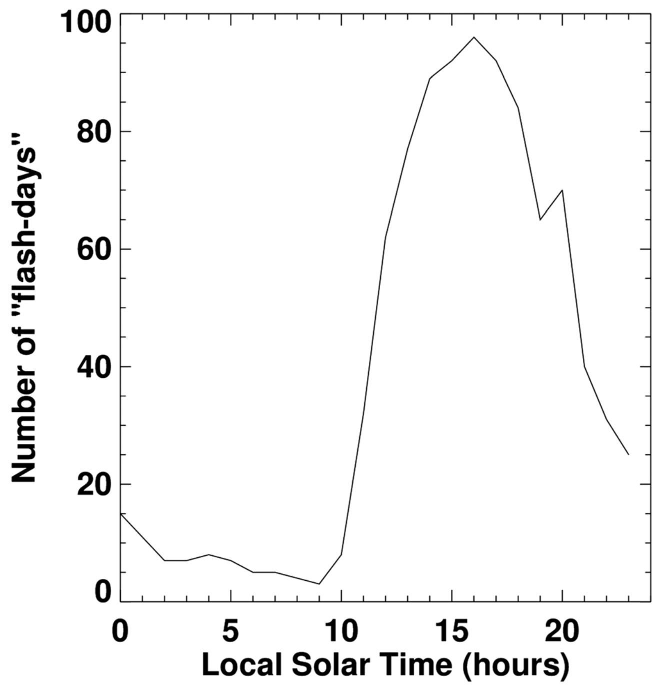

Figure 3. Number of flash-days contributing to each LST hourly bin.

day-to-night transition, most evident after the local sunrise (~06:00 LST) when the source altitude increases from ~4 km at sunrise to ~7 km by ~10:00–15:00 LST. This observation likely relates to the dissipation of the transitional/nocturnal boundary layer discussed in the Introduction section and demonstrates the vertical convective growth and subsequent electrostatic discharges evident in the VHF spectrum.

Interestingly, the night-to-day transition shown in Figures 2c and 2d reveals additional characteristics During the nighttime (daytime) hours we observe more (less) horizontally/vertically extended flashes. In particular, the horizontal/vertical extents are larger during periods preceding and following the peak in flash count (Figure 2a), reaching a maximum around local sunrise (Figures 2c and 2d), and a minimum that temporally coincides with the afternoon flash count maximum. This constitutes an important finding of the previous analysis, in the context that it would have been otherwise unnoticed had the flash counts been considered exclusively (Figure 2a). Given that the flash size characteristics and counts appear to follow opposite trends between ~10:00 and 20:00 LST (linear correlation coefficient ~ -0.8, not shown), it could be argued that the two parameters exhibit an "inverse" relationship. However, the relationship is more complex when viewed for the entire 24 h day given that during the late night (00:00 LST) to early morning hours (~07:00 LST), the diurnal flash activity (Figure 2a) remains practically constant (i.e., having less than ~1% variation), whereas the flash size characteristics exhibit their maximum variation (Figures 2c and 2d).

Given the temporally limited data set, one could argue that the results presented in Figure 2 might not capture the full meteorological variability of the region, or account for all types of storms. This could be particularly true for nighttime hours that exhibit the lowest flash counts (see Figure 2a). As a result, the diurnal averages shown in Figures 2b and 2d might be biased from the sampling of storm(s) of a certain type (e.g., multichannel seismic, where spatially extended flashes would be expected; *Carey et al.*, 2005).

Since this study does not engage in individual storm identification (i.e., storm tracking), we compute the number of individual "flash-days" that contribute to the SPLMA flash counts for each hour (Figure 3). Figure 3 indicates what has been already highlighted in Figure 2a, that is, the majority of the contributing flash-days are found during the peak in afternoon convection. Figure 3 also indicates that all nighttime-early morning periods (00:00–09:00 LST) include 5–10 flash-days apiece, except for 09:00 LST (3 flash-days). While it could be argued that for these periods the flash-day number might still suggest inadequate sampling, Figure 3 shows that the data clearly contain multiple storms (i.e., more than one or two) during each hour.

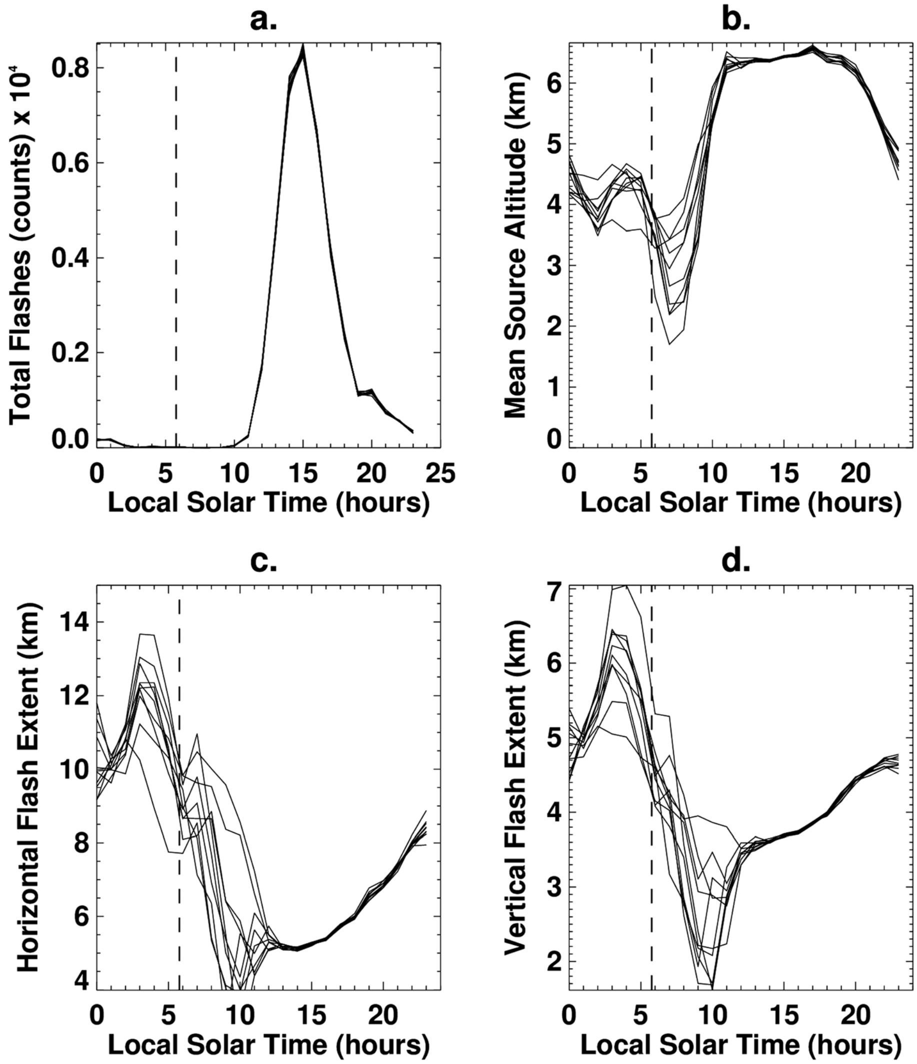

Figure 4. Same as Figure 2 but for 10 realizations that randomly select a subset of the original flash data set (100,000) between 0 and 40 km from the SP LMA center.

Additionally, supportive arguments for the representativeness of the findings herein stem from the following observations:

1. There is a consistent (i.e., monotonic) trend from the high flash-days periods (e.g., 18:00–23:00 LST, i.e., deemed as more representative) to the low flash-days periods (e.g., 00:00–05:00 LST, i.e., deemed as less representative)
2. As previously discussed, the behavior of the mean source altitude during, e.g., 03:00–09:00 LST, relates to a physical mechanism that has a well-established diurnal component (i.e., boundary layer night-to-day transition, see Introduction section)
3. The RMS uncertainties (~50–60 m) are significantly smaller than the kilometer-scale diurnal variations in size shown in Figure 2.

Another possible caveat pertaining to the representativeness of the findings of Figure 2 is that SPLMA (as well as any other LMA) relies on "line of sight" data acquisition (i.e., VHF sources are sampled only at higher altitudes as we move farther away from the network center [*Thomas et al.*, 2004]). To further ensure the statistical robustness of the results shown in Figures 2b–2d we dissect our data set and examine 10 random selections of 100,000 flashes (i.e., approximately one fourth of our initial data set). These are further grouped in two concentric areas around the SPLMA center, 0–40 km and 40–80 km. The resulting ranged-binned diurnal variation "ensemble" is shown in Figures 4 and 5. Although the periods with relatively lower flash

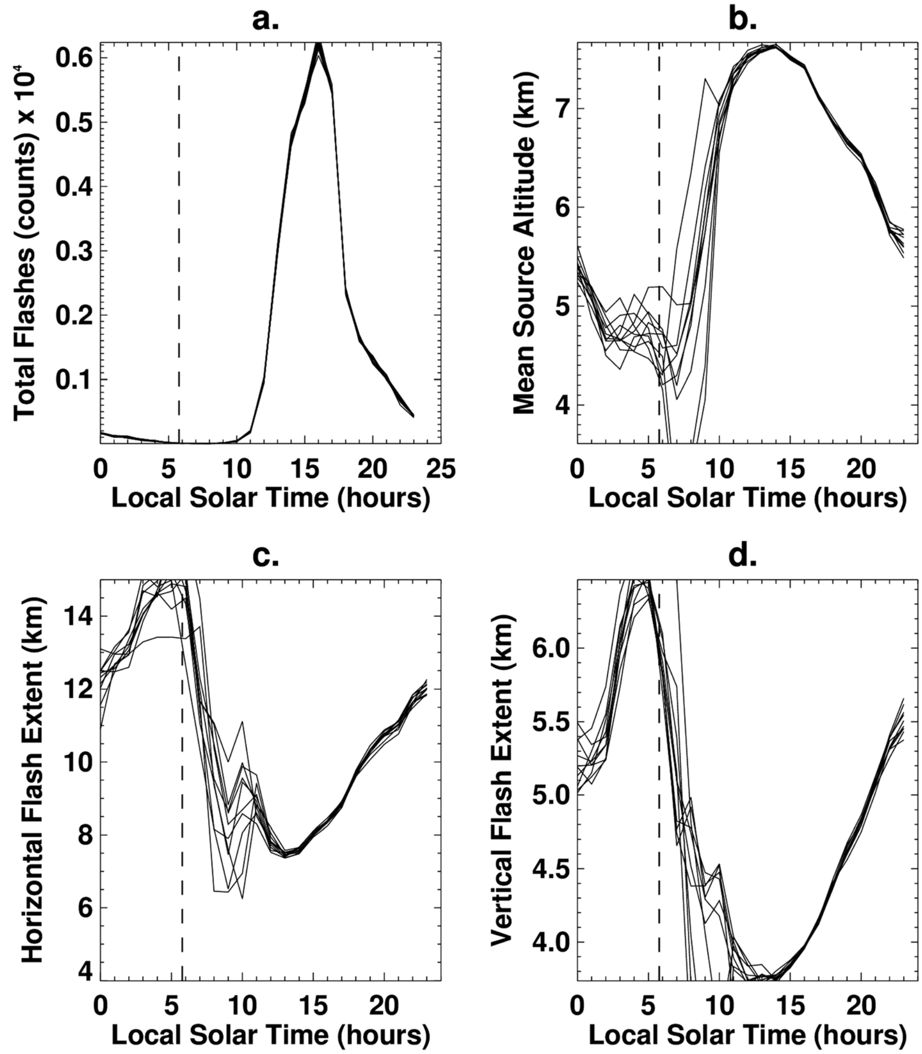

Figure 5. Same as Figure 3 but for 40–80 km from the SP LMA center.

counts exhibit more noise (e.g., 07:00–09:0 LST in Figures 4 and 5), the overall diurnal trends agree with the findings noted when the entire data set was considered (see Figure 2). Note that Figures 5b–5d show on average higher values for flash mean altitude, horizontal, and vertical extents, which is explained by the greater distance from the SPLMA center (i.e., dependence on line of sight).

To further explore the previous findings, we compute the joint histograms of the horizontal and vertical extents for every LST hourly bin (Figure 6). For the nighttime through the morning periods (~20:00–10:00 LST), the horizontal spans of flashes are on average approximately double (~9–10 km; Figure 5) their respective vertical spans (~4–5 km; Figure 6). Conversely, during the time period leading up to the flash count maximum (~13:00–17:00 LST), the flashes become relatively shorter and more symmetric (i.e., the differences between the horizontal and vertical dimensions for the majority of the flashes are reduced, see Figure 6). We acknowledge that the hourly bins with low flash counts (e.g., 07:00–09:00 LST, < ~100 flashes, see Figure 2) inevitably limit the representativeness of the data set. Nevertheless, the above-mentioned behavior is also evident for hourly bins independent of the respective number of flashes (low or high).

4. Discussion

This study has documented a diurnal component in the lightning flashes spatial characteristics derived from the SPLMA. Late-night to morning (afternoon) storms clearly exhibit spatially extended flashes, even during

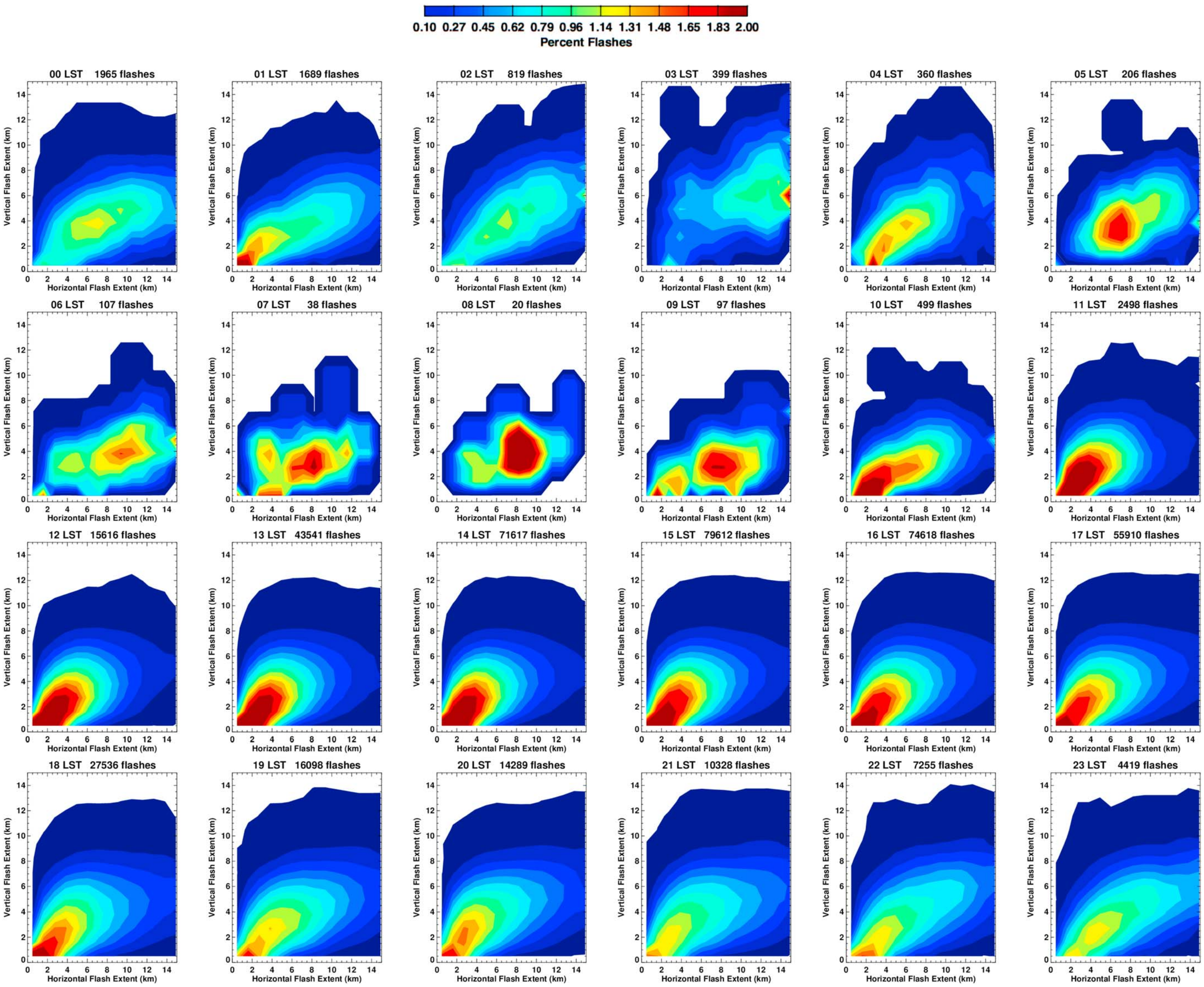

Figure 6. Joint histogram contour plot of flash vertical (*y* axis, in meters) and horizontal (*x* axis, in meters) extents for hourly diurnal segments. The color bar indicates the flash counts percentage in each LST hourly bin.

the period where the diurnal flash counts remain rather constant. Therefore, an important claim of this work is that the storm-based results by *Bruning and MacGorman* [2013] might also exhibit a strong climatological diurnal component. The study further suggests that the transition from local sunrise to the afternoon convective maximum involves surface heating and updraft invigoration that carries more moisture in the mixed-phase and results in higher concentrations of the necessary lightning-producing ingredients (i.e., graupel, ice crystals, and supercooled water, see *Emersic and Saunders*, 2010, and references therein). It is reasonable to hypothesize that the consequent particle collisions in the afternoon storms lead to more frequent but more spatially restricted flash discharges, given that the charge regions of opposite polarity are in closer proximity, as a result of the more rigorous mixing within the thundercloud. Consistent with this and the findings in Figure 6, the stronger afternoon precipitation mechanism and related latent heat release combined with the more vigorous turbulent updrafts can promote a more heterogeneous charge distribution [*Colgate*, 1969] through smaller eddies, leading to spatially "shorter" flashes of comparable horizontal/vertical extents [*Bruning and MacGorman*, 2013].

By reversing the previous hypothesis, we argue that the storms occurring in late evening through morning hours have less capacity for turbulent mixing than the afternoon storms. The cloud mixing processes are further suppressed by the limited precipitation-based latent heat release. Consequently, the thundercloud charging process is slower, leading to sparser and less frequent particle collisions, hence limiting the flash discharge rates [*Moore and Vonnegut*, 1977; *Livingston and Krider*, 1978; *Koshak and Krider*, 1989; *Mach et al*., 2011]. As a result, it would be reasonable to assume that the storms occurring during this diurnal segment, given the weakening of vertical turbulent mixing and greater influence of midlevel winds, distribute the cloud charge in a more stratified manner, resulting in flashes of larger horizontal/vertical spans. Examples of these would be the observed large horizontal IC flashes termed "anvil crawlers" [*Fuelberg et al*., 2014] or CG lightning flashes in mesoscale stratiform precipitation [*Lang et al*., 2004]. This cycle is disrupted around sunrise, when the surface heating gradually rebuilds the vertical moisture transport and invigorates vertical mixing. The above tentative claims are best supported by examining the spatial characteristics of flashes on a diurnal basis, instead of by an examination of the diurnal variability of flash counts. This last observation constitutes one of the key findings of the present study.

Arguably, the previous speculations can be thought of as a simplified explanation of a multiparametric problem that involves the thunderstorm charging mechanism. For instance, the relationship between turbulence regime and charging rates may well be far more complex than the mechanism proposed herein. For example, one could speculate that high collision rates can occur throughout the convective updraft, along a vertical path where turbulent eddies are present in varying magnitudes. Another parameter that could play a role is the altitude at which these collisions take place, the dielectric characteristics of the aerosol content but most importantly whether the microphysics are favorable for initiating a lightning discharge. In turn, the flash length would also be dependent on the vertical and horizontal cloud dimensions. An electrical analogue would be a large capacitor able to produce larger sparks between the oppositely charged plates compared to a capacitor of smaller dimensions [*Bruning and MacGorman*, 2013]. It is possible that alternative mechanisms from those described above (and references herein) will be present on a storm scale but also on a diurnal basis over other regions worldwide. As a result, this study cannot claim that the featured results are expected to be universally typical or representative of all storms. However, they are interesting on their own merits irrespective of whether they represent more widespread average diurnal processes. To further explore these topics we are currently expanding our research to include spatial flash characteristics for much larger LMA climatological data sets across the Contiguous United States (CONUS), which will also consider ground-based weather radar observations.

The observations presented in this paper may help explain not only a part of the recent findings by *Chronis et al*. [2015b] but also the results discussed in *Orville* [1990]. In *Chronis et al*. [2015b] the authors document a strong diurnal component in the CG first return-stroke peak current, I, over the CONUS that exhibits a marked similarity to the diurnal variation of the vertical flash extents shown here in Figure 2d. As discussed in *Chronis et al*. [2015b, and references therein], the return stroke peak current I depends on the neutralization of the deposited CG leader charge and is given by $I = v\,\lambda(z)$, where v is the return stroke speed and $\lambda(z)$ is the linear charge density along an assumed vertical CG leader channel's vertical length, z. Although the LMAs are not very efficient in observing CG leaders, we postulate that the diurnal variations in I found in *Chronis et al*. [2015b] may be linked to the CG flash vertical extents, via a postulated positive correlation between flash channel extent and channel linear charge density. However, the latter would require more in depth analysis that is currently beyond the scope of this paper. Also, in light of the fundamental relationship between I, flash extent, and the production of lightning-related nitrogen oxides, the findings in this study may also be relevant to air quality modeling efforts [*Koshak et al*., 2014].

Acknowledgments
The first author acknowledges the support by Steve Goodman and the GOES-R System Program as part of the Proving Ground and Risk Reduction programs. The authors would also like to extend their appreciation to Ken Cummins for the insightful comments. The CHUVA data can be freely accessed at http://chuvaproject.cptec.inpe.br/portal/noticia.ultimas.logic. This paper has been greatly improved by the constructive suggestions of anonymous reviewers.

References

Abarca, S. F., K. L. Corbosiero, and T. J. Galarneau Jr. (2010), An evaluation of the Worldwide Lightning LocationNetwork (WWLLN) using the National Lightning Detection Network (NLDN) as ground truth, *J. Geophys. Res.*, *115*, D18206, doi:10.1029/2009JD013411.

Bailey, J. C., L. D. Carey, R. J. Blakeslee, S. J. Goodman, R. I. Albrecht, C. A. Morales, and O. Pinto Jr. (2011), São Paulo Lightning Mapping Array (SP-LMA): Deployment and plans, Proc. 14th Int. Conf. on Atmospheric Electricity, Rio de Janeiro, Brazil, International Commission on Atmospheric Electricity. [Available at http://www.icae2011.net.br/index.pt.html.]

Beirle, S., W. Koshak, R. Blakeslee, and T. Wagner (2014), Global patterns of lightning properties derived by OTD and LIS, *Nat. Hazards Earth Syst. Sci.*, *14*, 2715–2726, doi:10.5194/nhess-14-2715-2014.

Betts, A. K., J. D. Fuentes, M. Garstang, and J. H. Ball (2002), Surface diurnal cycle and boundary layer structure over Rondiro, Brazil, International C, *J. Geophys. Res.*, *107*(D20), 8065, doi:10.1029/2001JD000356.

Blakeslee, J. R., J. C. Bailey, L. D. Carey, S. J. Goodman, S. D. Rudlosky, R. Albrecht, C. A. Morales, E. M. Anselmo, J. R. Neves (2013), Sao Paulo Lightning Mapping Array (SP-LMA): Network Assessment and analyses for intercomparison studies and GOES-R proxy activities, CHUVA Workshop, August 08–10, 2013, São Paulo, SP Brazil.

Bruning, E. C., and D. R. MacGorman (2013), Theory and observations of controls on lightning flash size spectra, *J. Atmos. Sci.*, *70*, 4012–4029.

Carey, L. D., and S. A. Rutledge (2003), Characteristics of cloud-to-ground lightning in severe and nonsevere storms over the central United States from 1989 1998, *J. Geophys. Res.*, *108*(D15), 4483, doi:10.1029/2002JD002951.

Carey, L. D., M. J. Murphy, T. L. McCormick, and N. W. S. Demetriades (2005), Lightning location relative to storm structure in a leading-line, trailing-stratiform mesoscale convective system, *J. Geophys. Res.*, *110*, D03105, doi:10.1029/2003JD004371.

Cecil, D. J., D. E. Buechler, and R. J. Blakeslee (2014), Gridded lightning climatology from TRMM-LIS and OTD: Dataset description, *Atmos. Res.*, *1350*, 404–414, doi:10.1016/j.atmosres.2012.06.028.

Changnon, S. A. (1988), Climatology of thunder events in the conterminous United States. Part I: Temporal aspects, *J. Clim.*, *1*, 389–398.

Christian, H. J., et al. (2003), Global frequency and distribution of lightning as observed from space by the Optical Transient Detector, *J. Geophys. Res.*, *108*(D1), 4005, doi:10.1029/2002JD002347.

Chronis, T. (2012), Preliminary lightning observations over Greece, *J. Geophys. Res.*, *117*, D03113, doi:10.1029/2011JD017063.

Chronis, T., E. Williams, E. Anagnostou, and W. Petersen (2007), Lightning as a precursor of tropical cyclogenesis, *Eos Trans. AGU*, *88*(40), 397, doi:10.1029/2007EO400001.

Chronis, T., L. D. Carey, C. J. Schultz, E. V. Schultz, K. M. Calhoun, and S. J. Goodman (2015a), Exploring the lightning jump characteristics, *Weather Forecast.*, *30*, 23–37, doi:10.1175/WAF-D-14-00064.1.

Chronis, T., K. Cummins, R. Said, W. Koshak, E. McCaul, E. R. Williams, G. T. Stano, and M. Grant (2015b), Climatological diurnal variation of negative CG lightning peak current over the continental United States, *J. Geophys. Res. Atmos.*, *120*, 582–589, doi:10.1002/2014JD022547.

Colgate, S. A. (1969), in *Planetary Electrodynamics*, edited by S. C. Coroniti and J. Hughes, pp. 144–145, CRC Press, New York.

Deierling, W., and W. A. Petersen (2008), Total lightning activity as an indicator of updraft characteristics, *J. Geophys. Res.*, *113*, D16210, doi:10.1029/2007JD009598.

Emersic, C., and C. P. R. Saunders (2010), Further laboratory investigations into the relative diffusional growth rate theory of thunderstorm electrification, *Atmos. Res.*, *98*, doi:10.1016/j.atmosres.2010.07.011.

Fuelberg, H. E., R. J. Walsh, and A. D. Preston (2014), The extension of lightning flashes from thunderstorms near Cape Canaveral, Florida, *J. Geophys. Res. Atmos.*, *119*, 9965–9979, doi:10.1002/2014JD022105.

Goodman, S. J., D. E. Buechler, P. D. Wright, and W. D. Rust (1988), Lightning and precipitation history of a microburst-producing storm, *Geophys. Res. Lett.*, *15*, 1185–1188, doi:10.1029/GL015i011p01185.

Holle, R. L. (2014), Diurnal variations of NLDN-reported cloud-to-ground lightning in the United States, *Mon. Weather Rev.*, *142*, 1037–1052.

Koshak, W. J., and E. P. Krider (1989), Analysis of lightning field changes during active Florida thunderstorms, *J. Geophys. Res.*, *94*(D1), 1165–1186, doi:10.1029/JD094iD01p01165.

Koshak, W. J., et al. (2004), North Alabama Lightning Mapping Array (LMA): VHF source retrieval algorithm and error analyses, *J. Atmos. Oceanic Technol.*, *21*, 543–558.

Koshak, W. J., H. S. Peterson, A. P. Biazar, M. Khan, and L. Wang (2014), The NASA Lightning Oxides Model (LNOM): Application to air quality modeling, *Atmos. Res.*, *135–136*, 363–369.

Lang, T. J., S. A. Rutledge, and K. C. Wiens (2004), Origins of positive cloud-to-ground lightning flashes in the stratiform region of a mesoscale convective system, *Geophys. Res. Lett.*, *31*, L10105, doi:10.1029/2004GL019823.

Livingston, J. M., and E. P. Krider (1978), Electric fields produced by Florida thunderstorms, *J. Geophys. Res.*, *83*, 385–401, doi:10.1029/JC083iC01p00385.

MacGorman, D., and C. D. Morgenstern (1998), Some characteristics of cloud to ground lightning in mesoscale convective systems, *J. Geophys. Res.*, *103*(D12), 14,011–14,023, doi:10.1029/97JD03221.

Mach, D., R. J. Blakeslee, and M. Bateman (2011), Global electric circuit implications of combined aircraft storm electric current measurements and satellite-based diurnal lightning statistics, *J. Geophys. Res.*, *116*, D05201, doi:10.1029/2010JD014462.

Mach, D. M., R. J. Blakeslee, M. G. Bateman, and J. C. Bailey (2010), Comparisons of total currents based on storm location, polarity, and flash rates derived from high-altitude aircraft overflights, *J. Geophys. Res.*, *115*, D03201, doi:10.1029/2009JD012240.

Machado, L. A., et al. (2014), The Chuva Project: How Does Convection Vary across Brazil?, *Bull. Am. Meteorol. Soc.*, *95*, 1365–1380.

McCaul, E. W., S. J. Goodman, K. M. LaCasse, and D. J. Cecil (2009), Forecasting lightning threat using cloud-resolving model simulations, *Weather Forecasting*, *24*, 709–729.

Moore, C. B., and B. Vonnegut (1977), The thundercloud, in *Lightning*, vol. 1, edited by R. H. Golde, pp. 51–98, Academic, San Diego, Calif.

Orville, R. E. (1990), Peak-current variations of lightning return strokes as a function of latitude, *Nature*, *343*, 149–151.

Orville, R. E., and G. R. Huffines (2001), Cloud-to-ground lightning in the United States: NLDN results in the first decade, 1989–98, *Mon. Weather Rev.*, *129*, 1179–1193.

Pinto, I. R. C. A., O. Pinto Jr., R. M. L. Rocha, J. H. Diniz, A. M. Carvalho, A. Cazetta Filho (1999), Cloud-to-ground lightning flashes in the southeastern Brazil in 1993, 2, Time variations and flash characteristics, *J. Geophys. Res.*, *104*, 31,381–31,387, doi:10.1029/1999JD900799.

Pinto, O., Jr., I. R. C. A. Pinto, J. H. Diniz, A. Cazetta Filho, L. C. L. Cherchiglia, and A. M. Carvalho (2003), A seven-year study about the negative cloud-to-ground lightning flash characteristics in the south- eastern Brazil, *J. Atmos. Sol. Terr. Phys.*, *65*, 739–748, doi:10.1016/S1364-6826(03)00077-4.

Rison, W., R. J. Thomas, P. R. Krehbiel, T. Hamlin, and J. Harlin (1999), A GPS-based three-dimensional light- ning mapping system: Initial observations in central New Mexico, *Geophys. Res. Lett.*, *26*, 3573–3576, doi:10.1029/1999GL010856.

Rudlosky, S. D., and H. E. Fuelberg (2010), Pre- and postupgrade distributions of NLDN reported cloud-to-ground lightning characteristics in the Contiguous United States, *Mon. Weather Rev.*, *138*, 3623.

Said, R. K., M. B. Cohen, and U. S. Inan (2013), Highly intense lightning over the oceans: Estimated peak currents from global GLD360 observations, *J. Geophys. Res. Atmos.*, *118*, 6905–6915, doi:10.1002/jgrd.50508.

Saunders, C. P. R. (1993), A review of thunderstorm electrification processes, *J. Appl. Meteorol.*, *32*, 642–655.

Saunders, C. P. R., H. Bax-Norman, C. Emersic, E. E. Avila, and N. E. Castellano (2006), Laboratory studies of the effect of cloud conditions on graupel/crystal charge transfer in thunderstorm electrification, *Q. J. R. Meteorol. Soc.*, *132*, 2653–2673.

Schultz, C. J., W. A. Petersen, and L. D. Carey (2011), Lightning and severe weather: a comparison between total and cloud-to-ground lightning trends, *Weather Forecasting*, *26*, 744–755.

Soden, B. (2000), The diurnal cycle of convection, clouds and water vapor in the tropical upper troposphere, *Geophys. Res. Lett.*, *27*, 2173–2176, doi:10.1029/2000GL011436.

Takahashi, T. (1978), Riming electrification as a charge generation mechan- ism in thunderstorms, *J. Atmos. Sci.*, *35*, 1536–1548.

Thomas, R. J., P. R. Krehbiel, W. Rison, S. J. Hunyady, W. P. Winn, T. Hamlin, and J. Harlin (2004), Accuracy of the lightning mapping array, *J. Geophys. Res.*, *109*, D14207, doi:10.1029/2004JD004549.

Villarini, G., and J. A. Smith (2013), Spatial and temporal variation of cloud-to-ground lightning over the continental U.S. during the period 1995–2010, *Atmos. Res.*, *124*, 137–148.

Williams, E. R., and S. J. Heckman (1993), The local diurnal variation of cloud electrification and the global diurnal variation of negative charge on the Earth, *J. Geophys. Res.*, *98*(D3), 5221–5234, doi:10.1029/92JD02642.

Williams, E., K. Rothkin, D. Stevenson, and D. Boccippio (2000), Global lightning variations caused by changes in thunderstorm flash rate and by changes in the number of thunderstorms, *J. Appl. Meteorol.*, *39*(12), 1965–1982, doi:10.1175/1520-0450(2001)040.

Zajac, B. A., and S. A. Rutledge (2001), Cloud-to-ground lightning activity in the contiguous United States from 1995 to 1999, *Mon. Weather Rev.*, *129*, 9991019.

Zhang, Y., and S. A. Klein (2013), Factors controlling the vertical extent of fair-weather shallow cumulus clouds over land: investigation of diurnal-cycle observations collected at the ARM Southern Great Plains site, *J. Atmos. Sci.*, *70*(4), doi:10.1175/JAS-D-12-0131.1.